Appendix VI

Regional Curves

BANKFULL HYDRAULIC GEOMETRY RELATIONSHIPS FOR NORTH CAROLINA STREAMS

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ABSTRACT

Bankfull hydraulic geometry relationships, also called regional curves, relate bankfull stream channel dimensions to watershed drainage area. This paper describes results of bankfull hydraulic geometry relationships developed for North Carolina Piedmont streams. Gage stations were selected with a minimum of 10 years of continuous or peak discharge measurements, no major impoundments, no significant change in land use over the past 10 years, and less than 20% impervious cover in the watershed. To supplement data collected in gaged watersheds, stable reference reaches in un-gaged watersheds were also included in the study. Cross-sectional and longitudinal surveys were measured at each study reach to determine channel dimension, pattern, and profile information. Log-Pearson Type III distributions were used to analyze annual peak discharge data for USGS gage station sites. Power function relationships were developed using regression analyses for bankfull discharge, channel cross-sectional area, mean depth, and width as functions of watershed drainage area. The bankfull return interval for the gaged watersheds ranged from 1.1 to 1.8, with a mean of 1.4 years. Continuing work will expand this database for the North Carolina Mountains, Piedmont, and Coastal Plain physiographic provinces.
Key Words: Hydraulic Geometry, Regional Curve, Bankfull, Flood Frequency Analyses

INTRODUCTION

Stream channel hydraulic geometry theory developed by Leopold and Maddock (1953) describes the interrelations between dependent variables such as width, depth and area as functions of independent variables such as watershed area or discharge. These relationships can be developed at a single cross section (at-a-station) or across many stations along a reach (Merigliano, 1997). Hydraulic geometry relationships are empirically derived and can be developed for a specific river or watershed in the same physiographic region with similar rainfall/runoff relationships (FISRWG, 1998).

Hydraulic geometry relationships are often used to predict channel morphology features and their corresponding dimensions. This paper describes the process used in North Carolina to develop hydraulic geometry relationships at the bankfull stage. Results for the rural Piedmont physiographic region are presented. Bankfull hydraulic geometry relationships, also called regional curves, were first developed by Dunne and Leopold (1978) and related bankfull channel dimensions to drainage area. Gage station

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analyses throughout the United States has shown that the bankfull discharge has an average return interval of 1.5 years or 66.7% annual exceedence probability (Dunne and Leopold, 1978; Leopold, 1994). A primary purpose for developing regional curves is to aid in identifying bankfull stage and dimension in un-gaged watersheds and to help estimate the bankfull dimension and discharge for natural channel designs (Rosgen, 1994).

FIELD INDICATORS OF BANKFULL STAGE

The correct identification of the bankfull stage in the field can be difficult and subjective (Williams, 1978; Knighton, 1984; and Johnson and Heil, 1996). Numerous definitions exist of bankfull stage and methods for its identification in the field (Wolman and Leopold, 1957; Nixon, 1959; Schumm, 1960; Kilpatrick and Barnes, 1964; and Williams 1978). The identification of bankfull stage in the humid Southeast is especially difficult because of dense understory vegetation and long history of channel modification and subsequent adjustment in channel morphology. It is generally accepted that bankfull stage corresponds with the discharge that fills a channel to the elevation of the active floodplain. The bankfull discharge is considered to be the channel forming agent that maintains channel dimension and transports the bulk of sediment over time. Field indicators include the back of point bars, significant breaks in slope, changes in vegetation, the highest scour line, or the top of the bank (Leopold, 1994). The most consistent bankfull indicators for streams in the rural Piedmont of North Carolina are the highest scour line and the back of the point bar. It is rarely the top of the bank or the lowest scour or bench.

STUDY AREA

North Carolina contains three major physiographic provinces: Mountains, Piedmont, and Coastal Plain. Because rainfall/runoff relationships vary by province and land cover, separate bankfull hydraulic geometry relationships are being developed for rural, suburban, and urban areas for each physiographic region (total of 9 regional curves). It may be necessary to further stratify the data for unique areas such as high rainfall areas in the Mountains and the Sandhills bordering the Piedmont and Coastal Plain. To date, data collection efforts have focused on the rural Piedmont and Mountains.

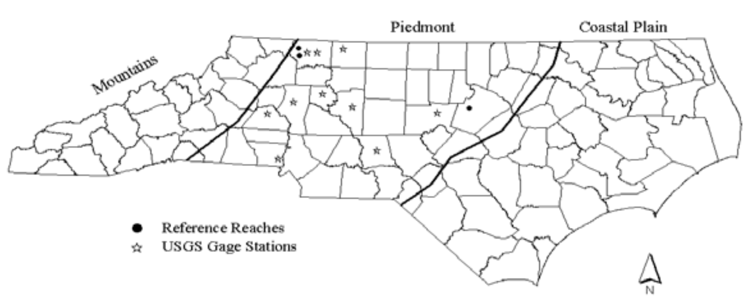

Figure 1: North Carolina map showing physiographic provinces with gaged and un-gaged study reaches.

USGS gage stations were identified with at least 10 years of continuous or peak discharge measurements, no major impoundments, no significant change in land use over the past 10 years, and less than 20% impervious cover over the watershed area. To supplement data collected in gaged watersheds, stable reference reaches in un-gaged watersheds were also selected for data collection using the same criteria. Figure 1 shows the relative locations of gaged and un-gaged study reaches.

METHODOLOGY

Data Collection

The following gage station records were obtained from the United States Geological Survey: 9-207 forms, stage/discharge rating tables, annual peak discharges, and established reference marks. At the gage, bankfull stage was flagged upstream and downstream of the gage station using the field indicators listed above. Once a consistent indicator was found, a cross-sectional survey was completed at a riffle or run near the gage plate. Temporary pins were installed in the left and right banks, looking downstream. The elevations from the survey were related to the elevation of a gage station reference mark. Each cross section survey started at or beyond the top of the left bank. Moving left to right, morphological features were surveyed including top of bank, bankfull stage, lower bench or scour, edge of water, thalweg, and channel bottom (Harrelson et al., 1994; U.S. Geological Survey, 1969). From the survey data, at-a-station bankfull hydraulic geometry was calculated.

For each reach, a longitudinal survey was completed over a stream length equal to at least 20 bankfull widths (Leopold, 1994). Longitudinal stations were established at each bed feature (heads of riffles and pools, maximum pool depth, scour holes, etc.). The following channel features were surveyed at each station: thalweg, water surface, low bench or scour, bankfull stage, and top of bank. The slope of a line fitted through the bankfull stage indicators was compared to a line of best fit through the water surface points. Leopold (1994) used this technique to verify the feature as bankfull if the two fitted lines were parallel and consistent over a long reach. The longitudinal survey was carried through the gage plate to obtain the bankfull stage. Using the current rating table and bankfull stage, the bankfull discharge was determined. The stream was classified using the Rosgen (1994) method.

Data Analyses

Log-Pearson Type III distributions were used to analyze annual peak discharge data for the USGS gage station sites. Procedures outlined in USGS Bulletin #17B Guidelines for Determining Flood Flow Frequency were followed (U.S. Geological Survey, 1982). USGS recommends Log-Pearson distributions because the log transformation removes positive skew from the data. Generalized skew coefficients and corresponding mean square errors for the Blue Ridge/Piedmont and Coastal Plain are 0.195 and 0.038, respectively (Pope, 1999). For this study, a range of exceedence probabilities from 0.9950 to 0.0100 was chosen. This range represents recurrence intervals between 1.005 and 100 years, with focus between the 1 and 2-year recurrence interval. The annual exceedence probability was calculated as the inverse of the recurrence interval. Exceedence probabilities were plotted as functions of corresponding calculated discharge measurements on log-probability paper, and a regression line was fit to the data. The bankfull discharge recurrence interval was then estimated from the graph.

Ungaged stream reaches were also surveyed to provide points in watersheds with relatively small drainage areas. To obtain a bankfull discharge (Q) estimate, at the stable ungaged watersheds, Manning's equation was used as:

$$Q = 1.4865 \, AR^{2/3} \, S^{1/2} / n \qquad (1)$$

where R = hydraulic radius, A = cross sectional area, S = average channel slope or energy slope, and n = roughness coefficient estimated using the bankfull mean depth and channel bed materials. Flood frequency analyses was not completed on ungaged streams.

RESULTS AND DISCUSSION

The at-a-station hydraulic geometry relationships for bankfull discharge, cross-sectional area, width, and mean depth as functions of watershed area for the rural Piedmont of North Carolina are shown in Figures 3a-d. These relationships represent 10 USGS gage stations and 3 un-gaged reaches ranging in watershed area from 0.2 to 128 mi^2. The best-fit regression equations and upper and lower 95% confidence limits are shown for each relationship. The power function regression equations and corresponding coefficients of determination are:

$$Q_{bkf} = 66.57 \, A_w^{0.89} \, ; (R^2 = 0.97) \qquad (2)$$

$$A_{bkf} = 21.43 \, A_w^{0.68} \, ; (R^2 = 0.95) \qquad (3)$$

$$W_{bkf} = 11.89 \, A_w^{0.43} \, ; (R^2 = 0.81) \qquad (4)$$

$$D_{bkf} = 1.50 \, A_w^{0.32} \, ; (R^2 = 0.88) \qquad (5)$$

where, Q_{bkf} = bankfull discharge (cfs), A_w = watershed drainage area (mi^{2}), A_{bkf} = bankfull cross sectional area (ft^2), W_{bkf} = bankfull width(ft), and D_{bkf} = bankfull mean depth (ft). Table 1 summarizes field measurements, hydraulic geometry, gage station analyses, and flood frequency analyses. The high coefficients of determination indicate good agreement between the measured data and the best-fit relationships. However, the wide range of the values included within the 95% confidence limits indicates the need for caution when using these relationships. For example, the bankfull cross-sectional area for a 10-mi^2 watershed ranges from approximately 60 to 180 ft^2 with a predicted value of 103 ft^2. The range of variability increases with increasing watershed area. This natural variability results from variations in average annual runoff, stream type (Rosgen, 1994), land use, and the natural variability of stream hydrology (Leopold, 1994). The bankfull return interval ranged from 1.09 to 1.80, with an average of 1.4 years. Dunne and Leopold (1978) reported a bankfull return interval of 1.5 years from a national study.

The relationships described in equations 2-5 represent data collected only in rural Piedmont streams in North Carolina. Ongoing work is being done in urbanized Piedmont watersheds and in streams throughout the Mountain and Coastal Plain provinces to compare with the existing relationships. Continuing data collection will ultimately result in a set of relationships for each physiographic province and sub-region, stratified by rainfall/runoff relationships.

CONCLUSION

Bankfull hydraulic geometry relationships are valuable to engineers, hydrologists, geomorphologists, and biologists involved in stream restoration and protection. They can be used to assist in field identification of bankfull stage and dimension in un-gaged watersheds. They can also be used to help evaluate the relative stability of a stream channel. Results of this study indicate good fit for regression equations of hydraulic geometry relationships in the rural Piedmont of North Carolina. However, users must be careful to consider the natural variability represented by the 95% confidence limits for these relationships. Further work is necessary to develop reliable relationships for other regions and rainfall/runoff conditions.

ACKNOWLEDGEMENTS

The NC Interagency Stream Restoration Task Force is developing bankfull hydraulic geometry relationships for all three physiographic regions in North Carolina. Special thanks go to task force members, Dani Wise, Ben Pope, Ray Riley, Sherman Biggerstaff, Jean Spooner, Carolyn Mojonnier, Rachel Smith, Mark Cantrell, Alan Walker, and Neil Woerner. The authors acknowledge the AWRA reviewers for their thorough review of this manuscript.

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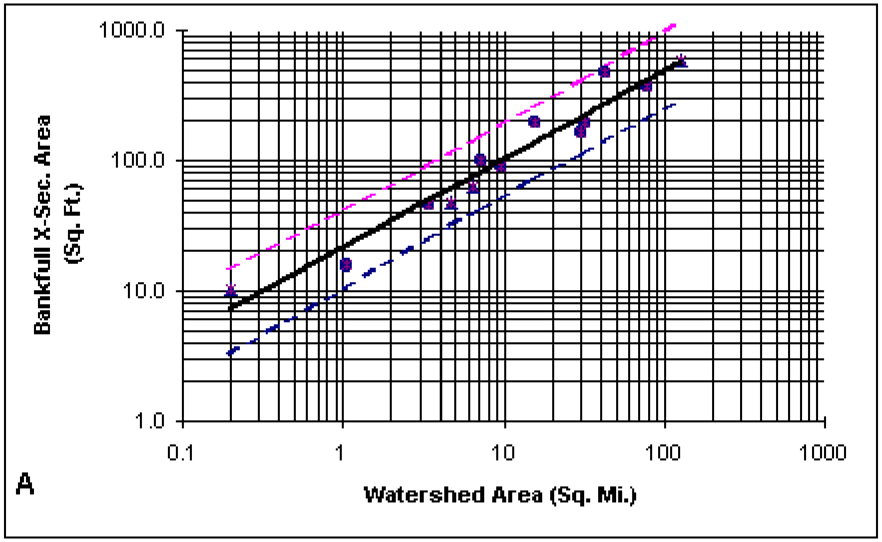
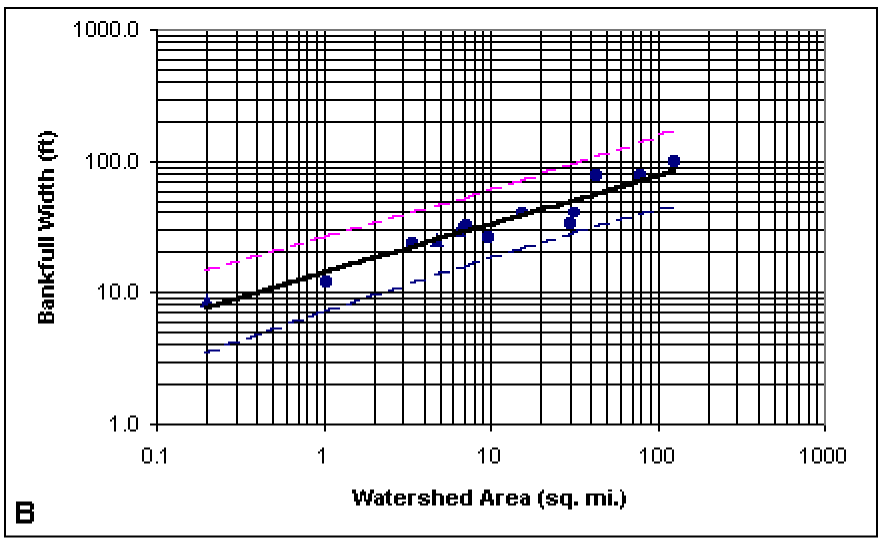
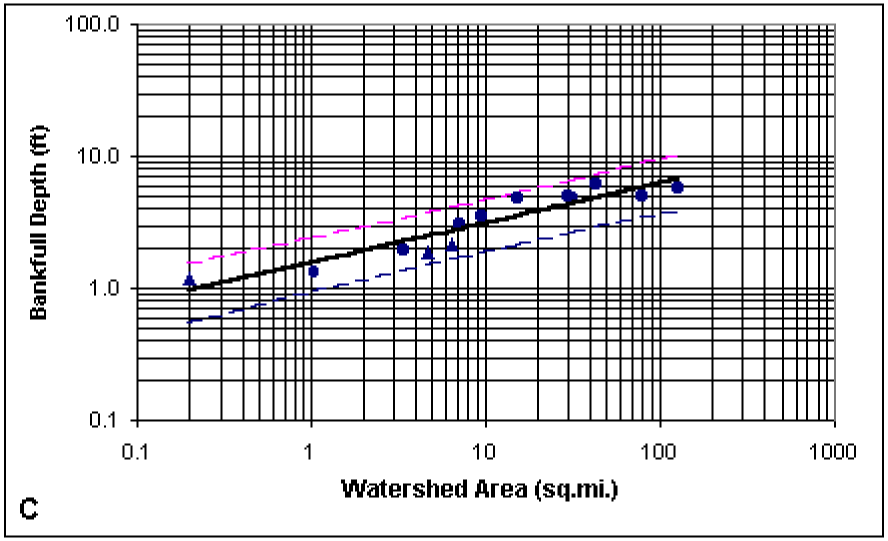
Stream Name	Gage Station ID	Drainage Area (mi^2)	Stream Type (Rosgen)	Bankfull Discharge (cfs)	Bankfull Xsec Area (ft^2)	Bankfull Width (ft)	Bankfull Mean Depth (ft)	Water Surface Slope (ft/ft)	Return Interval (Years)
Sal's Branch	Reference Reach	0.2	E4	55.4	10.4	8.7	1.2	0.0109	n/a
Humpy Creek	02117030	1.05	E5	83.0	15.8	12.0	1.3	0.0060	1.7
Dutchmans	02123567	3.44	C5	85.1	45.6	23.5	1.9	0.0170	1
Mill Creek	Reference Reach	4.7	E4	277	46.7	24.5	1.9	0.0080	n/a
Upper Mitchell River	Reference Reach	6.5	B4c	356	62.5	29.2	2.1	0.0095	n/a
Norwood Creek	0214253830	7.18	E5	253.7	98.8	32.0	3.1	0.0008	1.1
North Pott's Creek	02121180	9.6	E5	507.2	89.6	25.4	3.5	0.0012	1.7
Tick Creek	02101800	15.5	E	655.3	194	40.5	4.8	0.0005	1.3
Moon Creek	02075160	29.9	E5	708.8	162	33.0	4.9	0.0015	1.8
Long Creek	02144000	31.8	E5	1041	195	40.0	4.9	0.0010	1.4
Little Yadkin River	02114450	42.8	G5	2236	469	77.5	6.1	0.0018	1.4
Mitchell River	02112360	78.8	C	2681	377	77.0	4.9	0.0030	1.6
Fisher River	02113000	128	C3	3687	578	101	5.7	0.0023	1.4

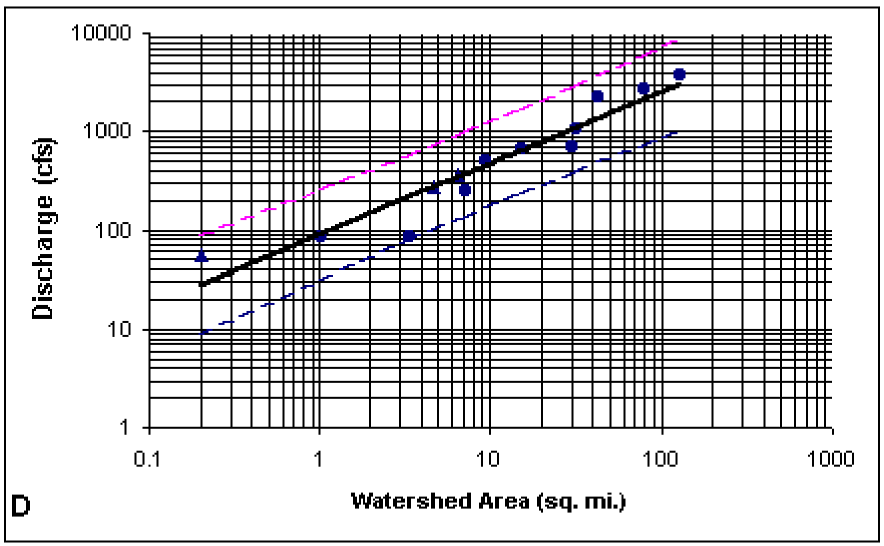
Table 1: Hydraulic geometry, survey summary, and flood frequency analyses for gaged and ungaged stream reaches.

Bankfull hydraulic geometry relationships for rural Piedmont North Carolina Streams. The four graphs represent: a) cross sectional area, b) width, c) depth, and d) discharge. The circles represent gage stations and the triangles represent ungaged streams. The outside dashed lines are the 95% confidence intervals for all the data points.






100.0
10.0
1.0
0.1
Bankfull Depth (ft)
0.1
1
10
100
1000
Watershed Area (sq.mi.)
C


10000
1000
100
10
1
Discharge (cfs)
0.1
1
10
100
1000
Watershed Area (sq. mi.)
D

BANKFULL REGIONAL CURVES FOR NORTH CAROLINA MOUNTAIN STREAMS

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ABSTRACT: Bankfull hydraulic geometry relationships, also called regional curves, relate bankfull stream channel dimensions and discharge to watershed drainage area. This paper describes preliminary results of bankfull regional curve relationships developed for North Carolina Mountain streams. Gage stations were selected with a minimum of 10 years of continuous or peak discharge measurements, no major impoundments, no significant change in land use over the past 10 years, and impervious cover ranges of <20%. To supplement data collected in gaged watersheds, stable reference reaches in un-gaged watersheds were also included in the study. Cross-sectional and longitudinal surveys were measured at each study reach to determine channel dimension, pattern, and profile information. Log-Pearson Type III distributions were used to analyze annual peak discharge data for USGS gage station sites. Power function relationships were developed using regression analyses for bankfull discharge, channel cross-sectional area, mean depth, and width as functions of watershed drainage area. The bankfull return interval for the rural mountain gaged watersheds ranged from 1.1 to 1.7 years, with a mean of 1.3 years. The mean bankfull return interval for rural North Carolina Piedmont gage stations was 1.4 years. Continuing work will expand this database for the North Carolina Mountain Physiographic Region.
KEY TERMS: Hydraulic Geometry, Regional Curve, Bankfull, Flood Frequency Analyses, Mountains

INTRODUCTION

Stream channel hydraulic geometry theory developed by Leopold and Maddock (1953) describes the interrelations between dependent variables such as width, depth and area as functions of independent variables such as discharge. Hydraulic geometry relationships are empirically derived and can be developed for streams in the same physiographic region with similar rainfall/runoff relationships (FISRWG, 1998). Bankfull hydraulic geometry relationships, also called regional curves, relate bankfull channel dimensions to drainage area (Dunne and Leopold, 1978). Gage station analyses throughout the United States have shown that the bankfull discharge has an average return interval of 1.5 years or 67% annual exceedence probability (Dunne and Leopold, 1978; Leopold, 1994). A primary purpose for developing regional curves is to aid in identifying bankfull stage and dimension in un-gaged watersheds and to help estimate the bankfull dimension and discharge for natural channel designs (Rosgen, 1994). This paper describes the process used in North Carolina to develop hydraulic geometry relationships at the bankfull stage. Preliminary results for rural watersheds in the Blue Ridge Mountain physiographic region are presented.

NORTH CAROLINA MOUNTAIN STUDY AREAS

North Carolina contains three major physiographic provinces: the Mountains, Piedmont, and Coastal Plain. The highest (100 inches) and the lowest (40 inches) mean annual precipitation in the Eastern U.S. is recorded in the North Carolina Mountains, both within the project study area and within 50 miles of each other. The steep mountain topography is also a factor in stream morphology, with the

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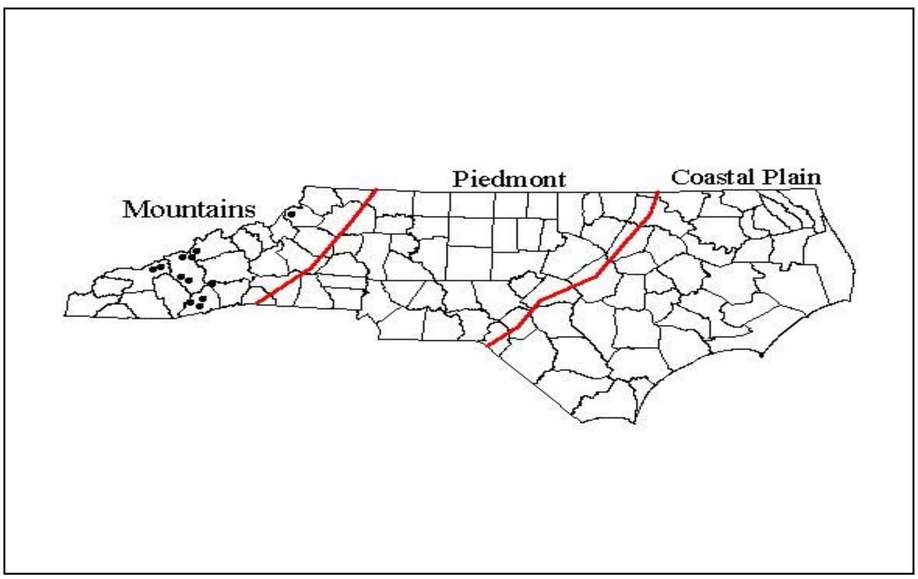
highest peak east of the Rocky Mountains at Mt. Mitchell (6,684 feet). In general, watersheds are more than 50% forested. Land cover dominated by human influences is locally high, but is less than 40% overall. Because rainfall/runoff relationships vary by province and land cover, separate bankfull hydraulic geometry relationships are being developed for rural and urban areas for each physiographic province. It may be necessary to further stratify the data for unique areas such as high rainfall areas in the Mountains and the Sandhills bordering the Piedmont and Coastal Plain.

USGS gage stations were identified with at least 10 years of continuous or peak discharge measurements, no major impoundments, no significant change in land use over the past 10 years, and impervious cover ranges of <20%. A geographic information system was used to analyze Thematic Mapper (TM) 1996 data to select watersheds with less than 20% impervious cover. To supplement data collected in gaged watersheds and provide points in smaller drainage areas, stable reference reaches in un-gaged watersheds were also selected using the same criteria. Project study sites are shown in Figure 1.

METHODOLOGY

Figure 1: North Carolina map showing physiographic provinces with Mountain study sites shown has dots.



Field Identification of Bankfull

Accurate identification of the bankfull stage in the field can be difficult and subjective (Williams, 1978; Knighton, 1984; and Johnson and Heil, 1996). Numerous definitions exist of bankfull stage and methods for its identification in the field (Wolman and Leopold, 1957; Nixon, 1959; Schumm, 1960; Kilpatrick and Barnes, 1964; and Williams 1978). The identification of bankfull stage in the humid Southeast is especially difficult because of dense understory vegetation and long history of channel modification and subsequent adjustment in channel morphology. It is generally accepted that bankfull stage corresponds with the discharge that fills a channel to the elevation of the active floodplain. The bankfull discharge is considered to be the channel-forming agent that maintains channel dimension and transports the bulk of sediment over time. Field indicators include the back of point bars, other significant breaks in slope, changes in vegetation type, the highest scour line, or the top of the bank (Leopold, 1994). The most consistent bankfull indicators for streams in North Carolina are the highest scour line and the back of the point bar. It is rarely the top of the bank or the lowest scour or bench.

DATA COLLECTION AND ANALYSES

The following gage station records were obtained from the United States Geological Survey: 9-207 forms, stage/discharge rating tables, annual peak discharges, and established reference marks. Bankfull stage was flagged upstream and downstream of the gage station using the field indicators listed above. Once a consistent indicator was found, a cross-sectional survey was completed at a riffle or run near the gage plate. Temporary pins were installed in the left and right banks, looking downstream. The elevations from the survey were related to the elevation of a gage station reference mark. Each cross section survey started at or beyond the top of the left bank. Moving left to right, morphological features were surveyed including top of bank, bankfull stage, lower bench or scour, edge of water, thalweg, and channel bottom (Harrelson et al., 1994). From the survey data, bankfull hydraulic geometry was calculated.

For each reach, a longitudinal survey was completed over a stream length approximately equal to 20 bankfull widths (Leopold, 1994). Longitudinal stations were established at each bed feature (heads of riffles and pools, maximum pool depth, scour holes, etc.). The following channel features were surveyed at each station: thalweg, water surface, low bench or scour, bankfull stage, and top of the low bank. The longitudinal survey was carried through the gage plate to obtain the bankfull stage. Using the current rating table and bankfull stage, the bankfull discharge was determined. Log-Pearson Type III distributions were used to analyze annual peak discharge data for the USGS gage station sites (Harman et al., 1999). Procedures outlined in USGS Bulletin #17B <u>Guidelines for Determining Flood Flow Frequency</u> were followed (U.S. Geological Survey, 1982). The bankfull discharge recurrence interval was then calculated from the flood frequency analyses. The stream was classified using the Rosgen (1994) method.

Ungaged, stable streams were also surveyed to provide points in watersheds with relatively small drainage areas. A stability analyses was completed before the stream was surveyed which included a bank erosion assessment, channel incision measurements, floodplain assessments, and review of historical maps and aerial photographs. To obtain a bankfull discharge (Q) estimate, at the stable ungaged watersheds, Manning's equation was used as:

$$Q = 1.4865\ AR^{2/3}\ S^{1/2} / n \qquad (1)$$

Where, R = hydraulic radius (ft), A = cross sectional area(ft^2), S = average channel slope or energy slope (ft/ft), and n = roughness coefficient estimated using the bankfull mean depth and channel bed materials. Flood frequency analyses was not completed on ungaged streams.

RESULTS AND DISCUSSION

The regional curves for the rural Mountains of North Carolina are shown in Figures 2a, b, c, and d. These relationships represent 9 USGS gage stations and 3 un-gaged reaches ranging in watershed area from 2.0 to 126 mi^2. The power function regression equations and corresponding coefficients of determination for bankfull discharge, cross sectional area, width, and mean depth are shown in Table 1.

Table 1: Power function regression equations for bankfull discharge and dimensions, where Q_{bkf} = bankfull discharge (cfs), A_w = watershed drainage area (mi^{2}), A_{bkf} = bankfull cross sectional area (ft^2), W_{bkf} = bankfull width(ft), and D_{bkf} = bankfull mean depth (ft).

Parameter	Power Function Equation	Coefficient of Determination R^2
Bankfull Discharge	$Q_{bkf} = 115.7A_w^{0.73}$	0.88
Bankfull Area	$A_{bkf} = 22.1A_w^{0.67}$	0.88
Bankfull Width	$W_{bkf} = 19.9A_w^{0.36}$	0.81
Bankfull Depth	$D_{bkf} = 1.1A_w^{0.31}$	0.79

Table 2 summarizes field measurements and hydraulic geometry. Table 3 summarizes bankfull discharge, flood frequency, and mean annual rainfall analyses. The moderately high coefficients of determination indicate good agreement between the measured data and the best-fit relationships. The vast range in mean annual precipitation (42 inches to 98 inches) explains the large degree of variability. Other sources of variability include the age of the forest, topography, land cover, soil type, runoff patterns, stream type and the natural variability of stream hydrology (Leopold, 1994). The bankfull return interval ranged from 1.1 to 1.9 years, with an average of 1.5 years. The mean bankfull return interval for rural North Carolina Piedmont gage stations was 1.4 years (Harman et al., 1999). Dunne and Leoplod (1978) reported a bankfull return interval of 1.5 years from a national study.

CONCLUSION

Bankfull hydraulic geometry relationships are valuable to engineers, hydrologists, geomorphologists, and biologists involved in stream restoration and protection. They can be used to assist in field identification of bankfull stage and dimension in un-gaged watersheds. They can also be used to help evaluate the relative stability of a stream channel. Results of this study indicate good fit for regression equations of hydraulic geometry relationships in the rural Mountains of North Carolina. Further work is necessary to develop additional data points to further explain the variability.

ACKNOWLEDGEMENTS

The NC Stream Restoration Institute is developing bankfull hydraulic geometry relationships for all three physiographic regions in North Carolina. Special thanks go to Angela Jessup, Richard Everhart, Ben Pope, Ray Riley, Sherman Biggerstaff, Kevin Tweedy, Jean Spooner, Carolyn Buckner, Barbara Doll, Rachel Smith, Louise Slate, and Brent Burgess. The authors acknowledge the AWRA reviewers for their thorough review of this manuscript.

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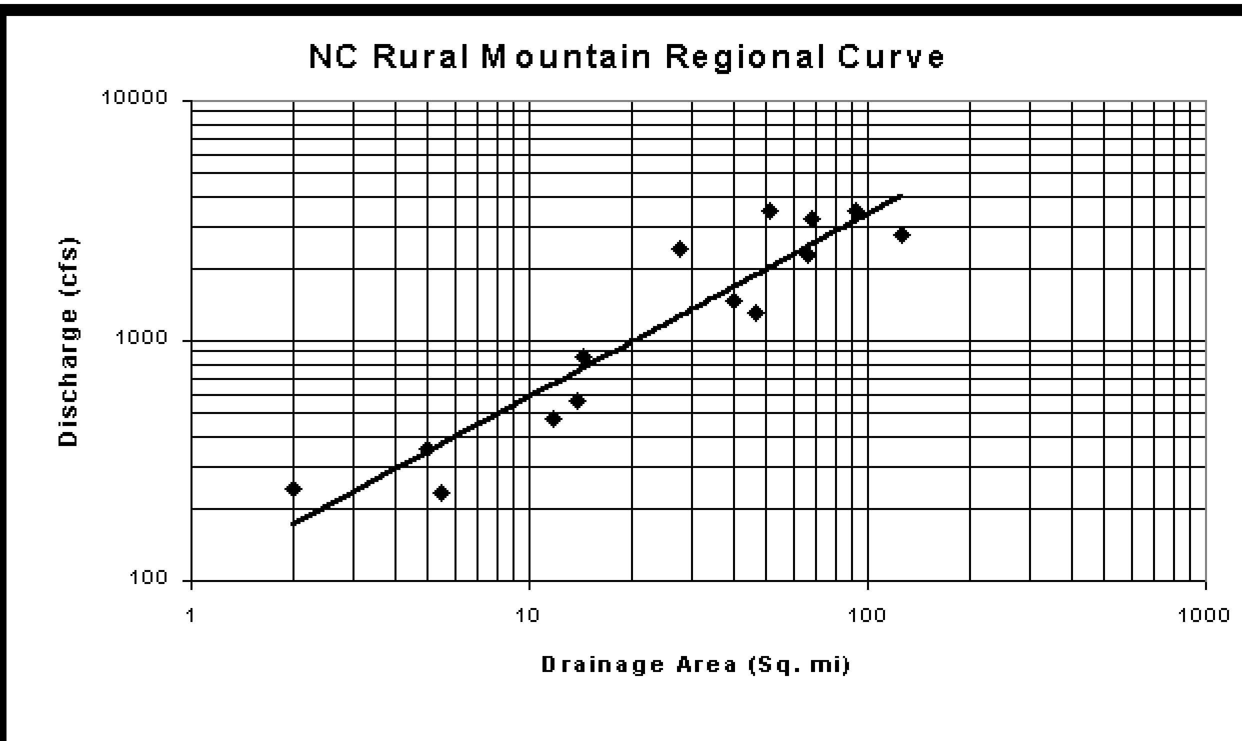
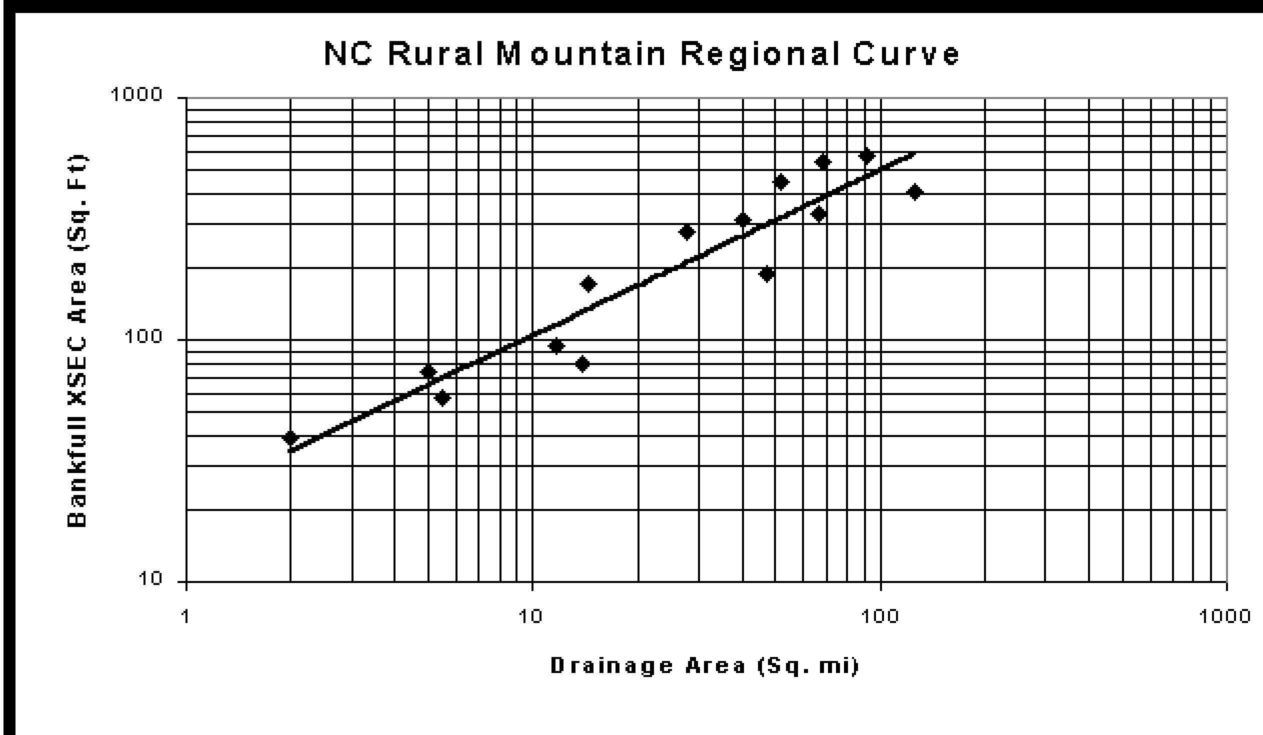
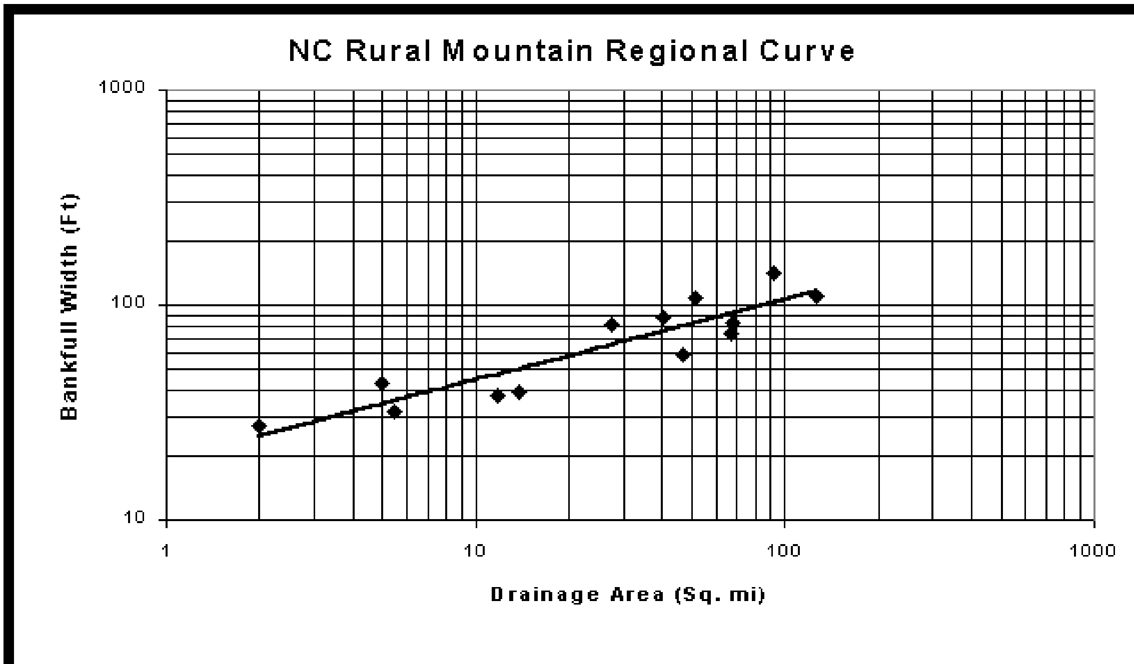
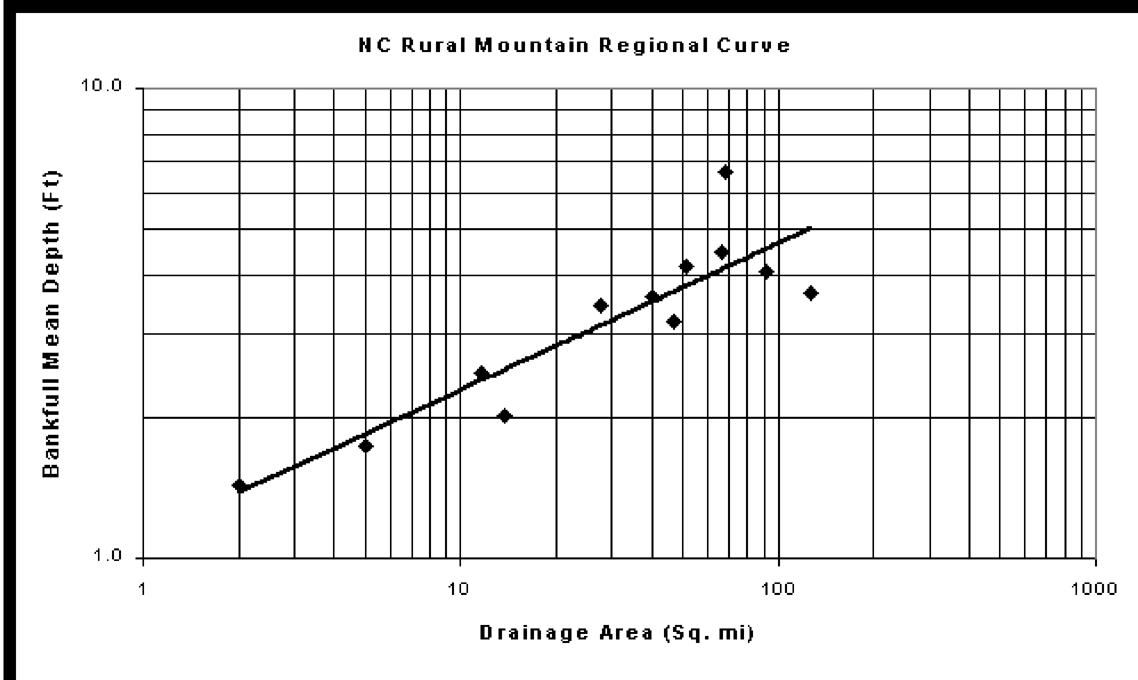
Stream Name	Gage Station ID	Stream Type (Rosgen)	Drainage Area (mi2)	Bankfull Discharge (cfs)	Bankfull Xsec Area (ft2)	Bankfull Width (ft)	Bankfull Mean Depth (ft)	Return Interval (Years)
French Broad at Rosman	3439000	E4	67.9	3226	544.9	82.4	6.6	1.3
Mills River	3446000	C4	66.7	2263	333	74.3	4.5	1.9
Davidson River	3441000	B4c	40.4	1457	316	87.6	3.6	1.1
Catheys Creek near Brevard	344000	B4c	11.7	470	94.2	38	2.5	1.67
West Fork of the Pigeon	3455500	B3c	27.6	2433	277.9	80.6	3.4	1.10
East Fork Pigeon River	3456500	B	51.5	3450	446.3	107	4.2	1.59
Watauga River	3479000	B4c	92.1	3492	572	140.3	4.1	1.25
Big Laurel	3454000	B4	126	2763	406	110.8	3.7	1.59
East Fork Hickey Fork Creek	n/a	B3a	2.0	242	39.3	27.4	1.4	n/a
Cold Spring Creek	n/a	B4	5.0	352	74.4	42.9	1.7	n/a
Caldwell Fork	n/a	B	13.8	560	79.3	39.4	2.0	n/a
Cataloochee	3460000	B4c	46.9	1320	186.9	58.7	3.2	1.60
Bee Tree	3450000	B3	5.46	231.5	56	32.1	1.7	1.85
North Fork Swannanoa	344894205	C3	14.5	855.7	170.6	69.3	2.5	


NC Rural Mountain Regional Curve
Discharge (cfs)
10000
1000
100
1
10
100
1000
Drainage Area (Sq. mi)


NC Rural Mountain Regional Curve
Bankfull XSEC Area (Sq. Ft)
1000
100
10
1
10
100
1000
Drainage Area (Sq. mi)



NC Rural Mountain Regional Curve
Bankfull Width (Ft)
1000
100
10
1
10
100
1000
Drainage Area (Sq. mi)



NC Rural Mountain Regional Curve
Bankfull Mean Depth (Ft)
10.0
1.0
1
10
100
1000
Drainage Area (Sq. mi)

Hydraulic Geometry Relationships for Urban Streams throughout the Piedmont of North Carolina

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William A. Harman[11], Rachel E. Smith[12] and Jean Spooner[2]

ABSTRACT: Hydraulic geometry relationships, or regional curves, relate bankfull stream channel dimensions to watershed drainage area. Hydraulic geometry relationships for streams throughout North Carolina vary with hydrology, soils, and extent of development within a watershed. This urban curve shows the bankfull features of streams in urban and suburban watersheds throughout the North Carolina Piedmont. Seventeen streams were surveyed in watersheds that had ten-percent or greater impervious cover. The watersheds had been developed long enough for the streams to redevelop bankfull features and had no major impoundments. The drainage areas for the streams ranged from 0.4 to 110.3 square kilometers. Cross-sectional and longitudinal surveys were conducted to determine the channel dimension, pattern and profile of each stream and power functions were fitted to the data. Comparisons were made with regional curves developed by Harman, et al. (1999) for the rural piedmont and enlargement ratios were produced. These enlargement ratios indicated a substantial increase in the hydraulic geometry for the urban streams in comparison to the rural streams. The study data was collected by NC State University, the University of North Carolina at Charlotte and Charlotte Storm Water Services. Urban regional curves are useful tools for applying natural channel design in developed watersheds. They do not, however, replace the need for field calibration and verification of bankfull stream channel dimensions.

KEY TERMS: Hydraulic Geometry, Regional Curve, Bankfull, Flood Frequency Analyses, Urbanization, Urban Water Management

INTRODUCTION

Decades of urban sprawl have degraded large numbers of streams throughout the country. For example, channelization, loss of riparian vegetation, floodplain restrictions and changes in hydrology have altered the dimension, pattern, and profile, and thereby the function, and habitat of many urban streams. As little as ten-percent impervious cover has been linked to stream degradation, with degradation becoming more severe as impervious cover increases (Schueler, 1995). Hammer (1973) found that the average annual flood, which equaled the 1.78-year storm, was doubled by an increase in population density of 5,500-6,000 persons per square mile from a rural condition. In addition, large contiguous impervious areas can significantly increase the size of a stream channel (Hammer 1972).

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Hammer (1972) developed stream channel enlargement ratios from a comparison of 50 urban and 28 rural watersheds in the Piedmont of Pennsylvania. His study showed an enlargement ratio for the cross-section of urbanized streams ranged from 0.7 to 3.8 for drainage areas ranging from 2.6 to 15.5 square kilometers in size.

A common sequence of physical adjustments has been observed in many streams following disturbance. This adjustment process is often referred to as channel evolution. Disturbance can result from channelization, increase in runoff, removal of streamside vegetation, as well as other changes that negatively affect stream stability. All of these disturbances are common in the urban environment. Several models have been used to describe this process of physical adjustment for a stream. Two models (Schumm et al. 1984, Simon 1989, and Simon an Downs 1995) have gained wide acceptance as being generally applicable for channels with cohesive banks (FISRWG 1998). Simons characterizes evolution in six steps, including 1) sinuous, premodified, 2) channelized, 3) degradation, 4) degradation and widening, 5) aggradation and widening, and 6) quasi equilibrium.

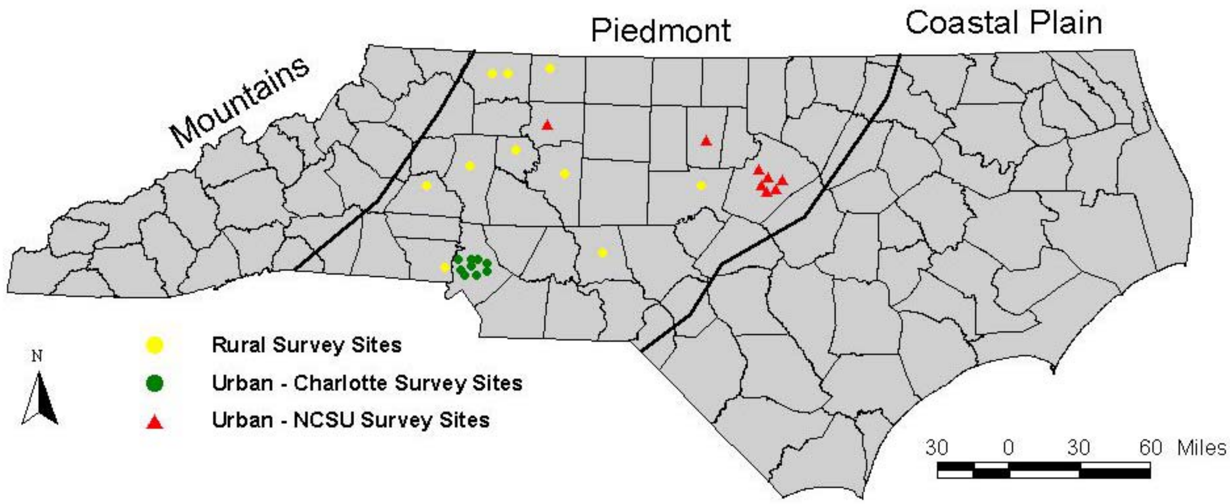
The channel evolution process is initiated once a stable, well-vegetated stream that frequently interacts with its floodplain is disturbed. Disturbance commonly results in an increase in stream power that causes degradation, often referred to as channel incision. Incision eventually leads to over-steepening of banks, and when critical bank heights are exceeded, the banks begin to fail and mass wasting of soil and rock leads to channel widening. Incision and widening continue moving upstream, commonly know as a head-cut. Eventually the mass wasting slows and the stream begins to aggrade. A new low-flow channel begins to form in the sediment deposits. By the end of the evolutionary process, a stable stream with dimension, pattern, and profile similar to those of undisturbed channels forms in the deposited alluvium. The new channel is at a lower elevation than its original form with a new floodplain constructed of alluvial material. The old floodplain remains a dry terrace (FISRWG. 1998). Most urban streams are at some stage of this evolutionary process. The time period required to reach a state of quasi equilibrium is highly variable and has not yet been determined.

Channelization and channel incision in addition can result in a loss of the water quality filtration and denitrifying function for the riparian buffers along many stream corridors. This is due to the lowering of the water table and the increase in the ratio of bank height to bankfull height associated with channelization and/or incision. In North Carolina, it was found that nitrogen removal capacity is lost as much of the groundwater flow to the stream passes beneath the buffer root system in these deeply incised stream systems (Kunickis, 2000).

Restoration and stabilization of urban streams is a priority focus for many federal, state and local government agencies and nonprofit groups. Many restoration practitioners strive to restore stability to disturbed streams by rebuilding natural stream characteristics, including a properly sized bankfull channel, adequate floodplain width, meanders, riffles, and pools. Stability is achieved when the stream has developed a stable dimension, pattern, and profile such that, over time, channel features are maintained and the stream system neither aggrades nor degrades (Rosgen, 1996). This restoration approach relies on the accurate identification of the bankfull channel dimension and discharge. Hydraulic geometry relationships that relate bankfull stream channel dimensions and discharge to watershed drainage area are therefore useful tools for stream restoration design. Because hydraulic geometry relationships for streams vary with hydrology, soils, and extent of development within a watershed, it is necessary to develop curves for various levels of development in each hydrophysiographic region. There are three primary physiographic regions in North Carolina: the Mountains, Piedmont, and Coastal Plain. The Piedmont is located between the Mountains and Coastal Plain and is characterized by rolling hills and wide alluvial valleys. The average annual precipitation is approximately 45 inches. Most Piedmont streams have moderate slopes that are controlled by bedrock outcrops (Horton et al., 1991). Hydraulic geometry data has already been developed for rural Piedmont North Carolina streams (Harman et al., 1999). This study focuses on identifying and comparing bankfull dimension and discharge of streams with urban watersheds to those with rural watersheds in the Piedmont.

Seventeen streams were surveyed in North Carolina Piedmont watersheds that had greater than ten-percent impervious cover. The watersheds had been developed long enough for the streams to redevelop bankfull features and had no major impoundments. The majority of the streams included in the study were in the process of recovering from past disturbances, including channelization or incision resulting from changes in hydrology due to urbanization. The reaches selected for survey were in or approaching quasi equilibrium. The drainage areas for the streams ranged from 0.4 to 110.3 square kilometers. The study includes data collected by NC State University, and by the University of North Carolina at Charlotte and the Charlotte Storm Water Services (Wilkerson, S.D., Master of Science thesis, Civil Engineering Department, UNC Charlotte). Streams are located in Chapel Hill, Raleigh, Durham, Winston-Salem and Charlotte. The locations of the survey sites are displayed on the map in Figure 1.

Figure 1. Survey Sites in North Carolina



This paper develops hydraulic geometry relationships for urban streams that have reached or are approaching quasi equilibrium in the channel evolution process. Urban curves for the Piedmont of North Carolina area were developed that compare bankfull cross-sectional area, discharge, width, and depth with drainage area. These relationships are compared to rural curves developed by Harman et al. (1999). Enlargement ratios comparing urban to rural curves are calculated to compare the magnitude of increases in the hydraulic geometry associated with urban impacts.

MATERIALS AND METHODS

U.S. Geological Survey (USGS) gaged urban streams were identified. Of the urban gaged streams, only those that met the study criteria were surveyed. The study criteria included: Piedmont streams with at least 10 percent impervious surface in their drainage area, no major impoundments, exhibiting bankfull indicators and having a stable riffle or run cross-section. Additional urban streams were identified through map analysis, local agency contacts and field reconnaissance. A consistent bankfull indicator was identified along each stream survey reach. Bankfull stage in general corresponds to the discharge that fills a channel to the elevation of the active floodplain. The bankfull discharge is considered to be the channel-forming flow, maintaining channel dimension and transporting the bulk of sediment over time (Leopold, 1994). Field indicators of bankfull stage include the back of point bars, significant breaks in slope, changes in vegetation, the highest scour line, or the top of the bank (Leopold, 1994). The most consistent bankfull indicators for Piedmont North Carolina streams are the highest scour line and the back of the point bar. The top of the bank or the lowest scour or bench is rarely an indicator of bankfull (Harman et al., 1999).

Cross-sectional and longitudinal surveys were conducted to determine the channel dimension, pattern and profile for each stream. Cross-sections were surveyed at a representative stable riffle or run that was not suffering from severe active erosion. Moving left to right looking downstream, morphological features were surveyed including top of bank, bankfull stage, lower bench or scour, edge of water, thalweg, and channel bottom (Harrelson et al., 1994; U.S. Geological Survey, 1969). Bankfull hydraulic geometry was calculated from the survey data at each riffle cross-section.

For each reach, a longitudinal survey was completed over a stream length equal to at least 20 bankfull widths (Leopold, 1994). Longitudinal stations were established at each bed feature (heads of riffles and pools, maximum pool depth, scour holes, etc.). The following channel features were surveyed at each station: thalweg, water surface, low bench or scour, bankfull stage, and top of bank. The slope of a line fitted through the bankfull stage indicators was compared to a line of best fit through the water surface points. Leopold (1994) used this technique to verify the feature as bankfull if the two lines were parallel and consistent over a long reach. At gaged stream sites, the longitudinal survey was carried through the gage plate to obtain the bankfull stage. The stream was classified using the Rosgen method (1994).

For gaged streams, the bankfull discharge and return period were determined using the USGS stage-discharge rating table and flood-frequency analysis, respectively. At least ten years of USGS gage discharge data, including annual peak flows, was necessary to develop flood frequency relationships. Log-Pearson Type III distributions were used to analyze the annual peak discharge data (U.S. Geological Survey, 1982). The generalized skew coefficient presented in the USGS Bulletin 17B was used for the flood frequency analysis (U.S. Geological Survey, 1982). The annual exceedence probability was calculated as the inverse of the recurrence interval. Exceedence probabilities were plotted as functions of corresponding calculated discharge measurements. From these flood frequency relationships a specific discharge can then be related to a return interval. In the case of Pigeon House Creek, Bushy Branch and Marsh Creek at Millbrook, the return interval was provided by a USGS flood frequency study of 32 small urban basins in North Carolina (U.S. Geological Survey, 1996). For this study, concurrent records of rainfall and runoff data collected in small urban basins were used to calibrate rainfall-runoff models. Historic rainfall records were used with the calibrated models to synthesize a long-term record of annual peak discharges. The synthesized record of annual peak discharges was then used in a statistical analysis to determine flood-frequency distribution. The study reported the discharges for the 2-, 5-, 10-, 25-, 50- and 100-year recurrence intervals. USGS provided the 1.11- and 1.25-year discharges for the three streams included in this study (Pope, B. F., Personal Communication, February 15, 2000, U.S. Geological Survey, Raleigh, N.C.).

For non-gaged streams, bankfull discharge was calculated using Manning's equation (Chow, 1959). Cross-sectional area and hydraulic radius were calculated using the cross-section survey data and a roughness coefficient was estimated according to Chow (1959). A sensitivity analysis comparing the discharge calculated using Manning's equation to the discharge produced by the gage data was conducted to validate the discharge method selected. The results of the sensitivity analysis are presented in Table 1.

Table 1: Discharge Sensitivity Analysis

Stream Name	Manning's Discharge (cms)	Gage Discharge (cms)	% Error
Pigeon House Branch	3	3	0.3
McMullen Creek @ Sharon View Road	34	28	19.6
Long Creek @ Oakdale	34	29	17.2
Irwin Creek near Billy Graham Pkwy	73	69	5.0
McAlpine @ Sardis Road	68	74	-8.4
Little Sugar Creek @ Archdale Road	130	124	4.5

For the streams surveyed by NC State University, existing EPA land use data was then used to estimate the impervious percentage for each stream's watershed. The EPA land use data is categorized by level two in the Anderson Land Use Classification System (Anderson et al., 1976) which includes residential, commercial, industrial, several vegetation types, pasture, cropland, industrial, and others (EPA, 1998). Natural Resource Conservation Service guidelines were used to assign an impervious cover percentage to each land use (NRCS, 1986). In the case of the Charlotte streams, Mecklenburg County's land use data was used to determine the impervious percentage. Distinct land use polygons were identified within each study watershed. Each land use area was assigned a land use code and each land use code was then assigned an average impervious surface percentage using the Natural Resource Conservation Service guidelines (NRCS, 1986).

For each stream, the bankfull cross-sectional area, discharge, width, and depth were plotted versus drainage area for the urban data. These relationships were found to be linear on a log scale, e.g., a power function was utilized. Confidence intervals (95%) on the individual observations and the regression relationships were also calculated. The same regression relationships and confidence intervals were also developed for the rural data presented by Harman et al. (1999). The urban curves were then compared to the rural data (Harman et al., 1999). A statistical regression test (Analysis of Covariance) using the PROC GLM procedure in SAS® was performed to test for homogeneity of slopes. That is, to test if there is statistical evidence that the slope was different for the urban as compared to the rural curves. If there was no evidence of slope differences, a pooled slope was assumed and parallel regression lines with different intercepts were calculated. Confidence intervals (95%) on the regression relations were also calculated. If there was evidence of different slopes, the error estimate around the regression lines was pooled and each line was allowed to have a different slope as well as intercept.

From a comparison of the urban and rural regional curves, it is possible to quantify the effect of urbanization by examining different enlargement ratios of a specific drainage area and x dimension, Ex, where: Ex = xu/xr, and xu =bankfull dimension of depth (Dbkf), width (Wbkf), cross-section (Abkf) or discharge (Qbkf) at a specific drainage area in urban areas, and xr= the same bankfull dimensions at a specific drainage area in rural areas. These enlargement ratios are based on comparing the dimensions obtained from the power functions (regional curves) fitted to the data and not comparison of the specific data. Relating the urban and rural region curves by plotting the enlargement ratios as a function of drainage area gives yet another power function.

RESULTS AND DISCUSSION

Table 2 summarizes field measurements and hydraulic geometry data for the urban streams. The rural regional curve data from Harman et al. (1999) are also included in Table 2. The relationships for bankfull discharge, cross-sectional area, width, and mean depth as functions of watershed area for the urban Piedmont of North Carolina are shown in Figures 2. The resulting 95% confidence intervals for both the individual observations and the regression relationship are also shown on Figure 2. In comparison the same hydraulic geometry relationships and associated confidence intervals for the rural Piedmont relationships from Harman et al. (1999) are shown in Figure 3. The urban relationships shown in Figure 2 represent nine USGS gage stations and eight un-gaged reaches ranging in watershed area from 0.4 to 110.3 square kilometers. The power functions regression equations and corresponding coefficients of determination for the urban curves are:

$$A_{bkf} = 3.02\ A_w^{\ 0.65} \qquad r^2=0.95 \qquad (1)$$

$$Q_{bkf} = 4.77\ A_w^{\ 0.63} \qquad r^2=0.94 \qquad (2)$$

$$W_{bkf} = 5.43\ A_w^{\ 0.33} \qquad r^2=0.88. \qquad (3)$$

$$D_{bkf} = 0.54\ A_{w.}^{\ 0.33} \qquad r^2=0.87 \qquad (4)$$

where, Q_{bkf} = bankfull discharge in cubic meters per second (cms), A_w = watershed drainage area in square kilometers (sq. km.), A_{bkf} = bankfull cross sectional area in square meters (sq. m.), W_{bkf} = bankfull width in meters (m), and D_{bkf} = bankfull mean depth in meters (m). The high coefficients of determination indicate good agreement between the measured data and the best-fit relationships. However, variability results from natural variations in average annual runoff, stream type (Rosgen, 1994), land use, and stream hydrology (Leopold and Maddock, 1953, Leopold, 1994). The bankfull return interval ranged from 1.1 to 1.5 for the gaged stream stations, with both the average and the median return interval at 1.3. Dunne and Leopold (1978) reported a bankfull return interval of 1.5 years from a national study.

The comparison of the urban data to the rural data to test for slope differences and to determine enlargement is shown on Figure 4. For each of the geometric relationships, there was no statistical evidence that the slopes for the urban and rural curves were different. Therefore, these regression relationships were calculated with the same slopes and different intercepts. In each relationship, there was a statistically significant difference between the intercepts; therefore, indicating significant shift, or enlargement, with the urban streams for similar drainage areas. The best-fit regression equations for the pooled data are shown for each urban and rural relationship (Figure 4). The resulting enlargement ratios are as follows:

$$E_{Abkf} = 2.65 \times (A_w)^{0.0} \qquad (5)$$

$$E_{Qbkf} = 2.91 \times (A_w)^{0.\ 0} \qquad (6)$$

$$E_{Wbkf} = 1.66 \times (A_w)^{0.0} \qquad (7)$$

$$E_{Dbkf} = 1.57 \times (A_w)^{0.0} \qquad (8)$$

It can be seen from these functions that the urban streams display a substantial increase in hydraulic geometry as compared to the rural counterparts. Since all the streams evaluated in this study were located in the same physiographic region, the Piedmont, it can be assumed that these enlargement ratios are a good representation of the flux in channel size, which can be expected as a rural watershed is developed. The drainage areas of the streams ranged from 0.4 to 110.3 square kilometers. There was no evidence that the enlargement ratios varied with watershed size (determined from the Analysis of Covariance which showed no evidence for different slopes on the log scale between the urban and rural curves.) Therefore, the exponent is estimated to be zero.

CONCLUSION

As expected, this study found enlarged bankfull dimension and discharge for urban streams versus rural streams with the same watershed area in the Piedmont region of North Carolina (see Figure 4). The increase in bankfull cross-sectional area between rural and urban streams is comparable to the increase calculated using Hammer's channel enlargement ratios. This study shows an enlargement ratio of the cross-section of urbanized streams of 2.6, which is comparable to Hammer's (1972) enlargement range of 0.7 to 3.8 found in similar sized watersheds. The enlargement ratio falls in the upper end of the range found by Hammer and show much less variability. The study also shows an increase in bankfull average depth with an increase in urbanization. This depth increase however does not represent an increase in pools. Rather, the streams surveyed were dominated by riffle and run and lacking good pool habitat. The increase in depth is merely a function of a larger channel that is carrying larger discharges.

Bankfull hydraulic geometry relationships are valuable to engineers, hydrologists, geomorphologists, and biologists involved in stream restoration and protection. They can be used to assist in field identification of bankfull stage and dimension in un-gaged watersheds. They do not, however, replace the need for field calibration and verification of bankfull stream channel dimensions. Results of this study indicate good fit for regression equations of hydraulic geometry relationships in the urban Piedmont of North Carolina.

Further work is necessary to develop reliable relationships for other regions and rainfall/runoff conditions. Additional data are being collected for the urban and suburban curves in Piedmont North Carolina in order to capture a broader range of stream types, drainage area impervious cover percentages and drainage area sizes throughout Piedmont North Carolina. Additional stratification of the data according to impervious percentage may be necessary. The current logarithmic scale used for presenting the data does not reveal significant variation between 17-80 percent impervious surface area.

Figure 2: Hydraulic geometry relationships of (a) bankfull cross-sectional area, (b) discharge, (c) width, and (d) depth compared to watershed area for urban streams in the North Carolina Piedmont.

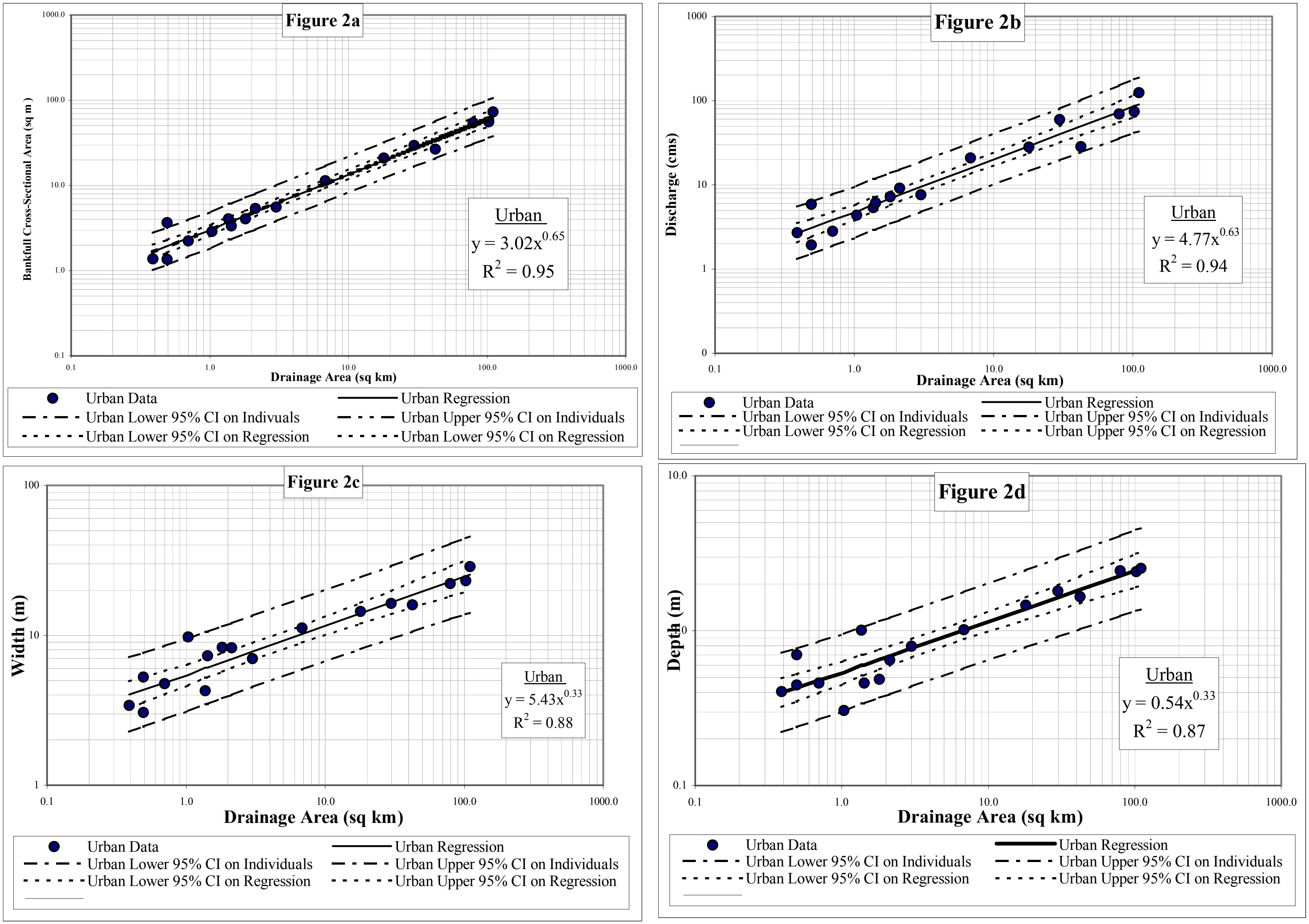


Figure 3: Hydraulic geometry relationships of (a) bankfull cross-sectional area, (b) discharge, (c) width, and (d) depth compared to watershed area for rural streams in the North Carolina Piedmont from Harman et al. (1999).

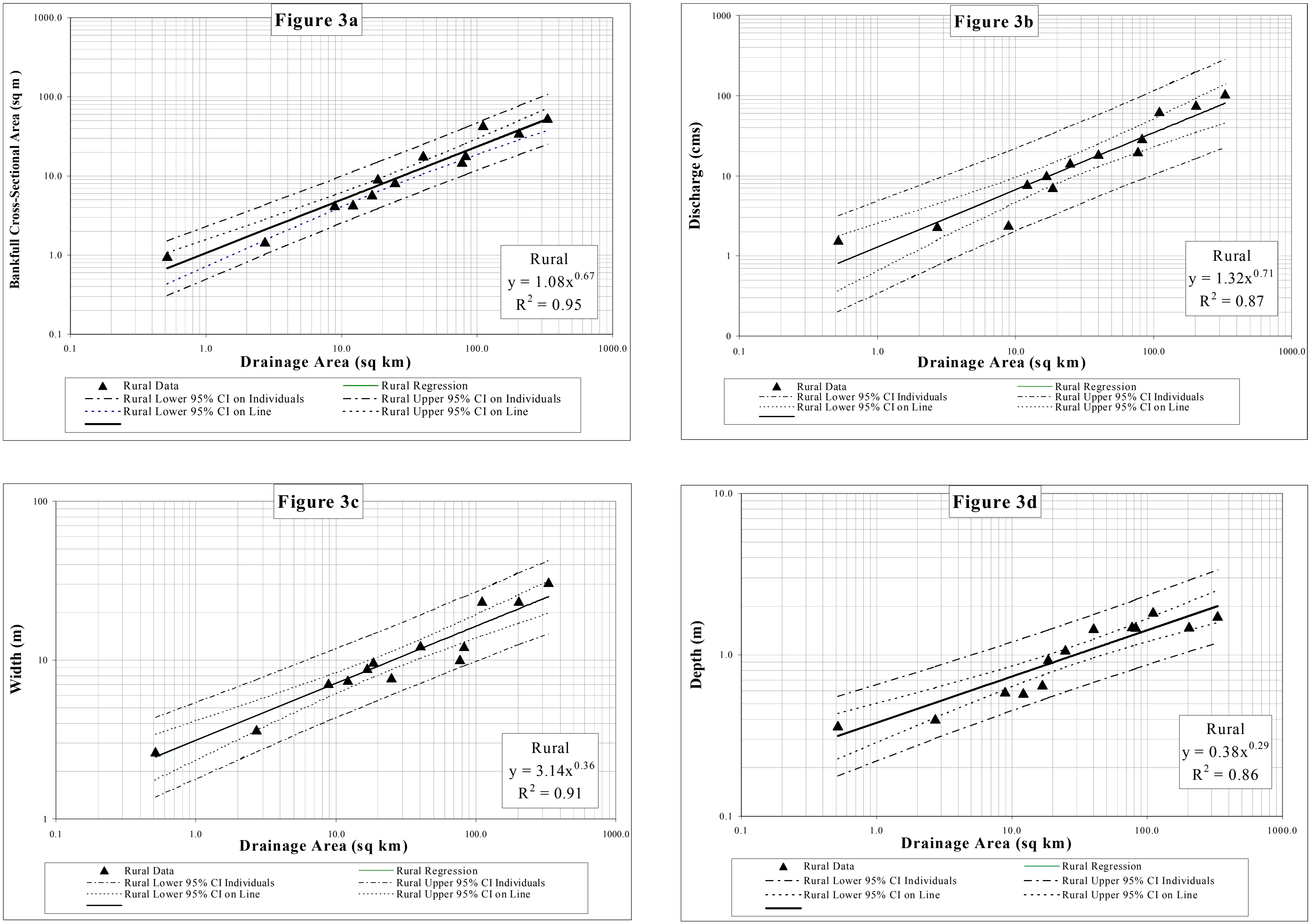


Figure 4: Comparison of urban versus rural regional hydraulic geometry relationships of (a) bankfull cross-sectional area, (b) discharge, (c) width, and (d) depth compared to watershed area for streams in the North Carolina Piedmont.

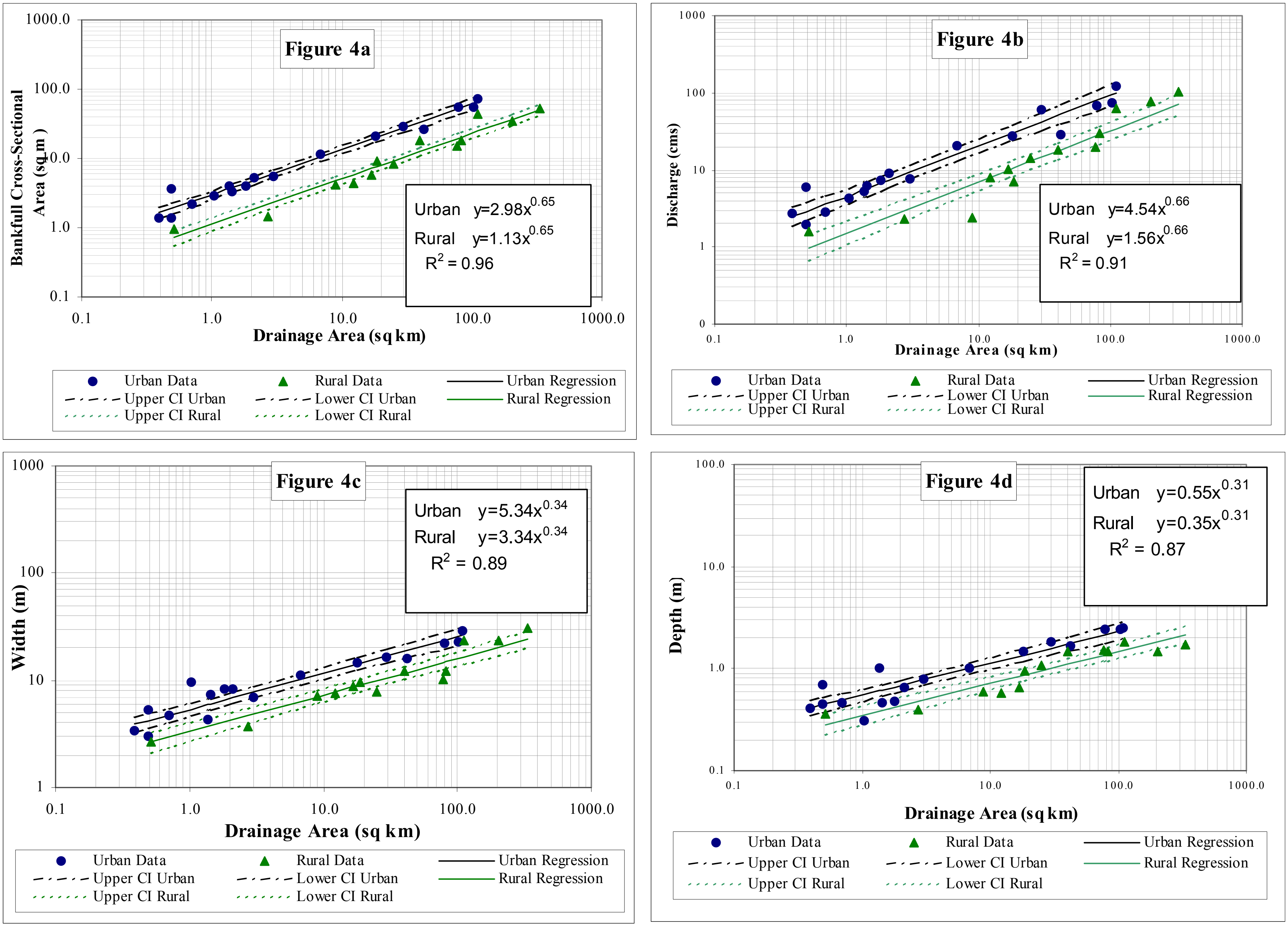


Table 2. Hydraulic geometry and survey summary for gaged and ungaged urban and rural stream reaches.

Survey Team *	Stream Name	Gaged Site	D.A. (sq.km.)	Bkfl X-sect. Area (sq. m.)	Discharge (cms)	Width (m)	Mean Depth (m)	Return Interval	Stream Type (Rosgen)	Impervious Surface Percentage
NCSU	Bushy Branch @ Schaub Dr.	No ***	0.5	1.4	2	3	0.4	1.5	E	20
NCSU	Bolin Creek Tributary	No	0.4	1.4	3	3	0.4		Eb	36
NCSU	Marsh Creek @ Millbrook	No ***	0.5	3.7	6	5	0.7	1.1	E	25
NCSU	Pigeon House Branch	Yes	0.7	2.2	3	5	0.5	1.1	E	47
NCSU	Rocky Branch 1	Yes **	1.0	2.9	4	10	0.3		F	80
C	Plaza-Midwood Creek at Masonic Dr.	No	1.4	4.1	5	4	1.0		E	26
NCSU	Brushy Fork Trib #2 (WS)	No	1.4	3.4	6	7	0.5		C	66
NCSU	Rocky Branch 2	Yes **	1.8	4.0	7	8	0.5		F	80
NCSU	Kentwood Park	No	2.1	5.4	9	8	0.6		Bc	54
C	Little Hope Creek @ Woodlawn	No	3.0	5.6	8	7	0.8		E	38
C	Little Hope Creek @ Seneca Place	Yes	6.8	11.3	21	11	1.0	1.4	E	41
C	McMullen Creek @ Sharon View Rd.	Yes	18.0	21.0	28	14	1.5	1.5	E	33
C	McMullen Creek @ Quail Hollow Rd.	No	29.8	29.5	59	16	1.8		E	32
C	Long Creek @ Oakdale	Yes	42.5	26.5	29	16	1.7	1.4	E	17
C	Irwin Creek near Billy Graham Pkwy	Yes	79.5	54.0	69	22	2.4	1.2	E	32
C	McAlpine @ Sardis Rd.	Yes	102.6	55.4	74	23	2.4	1.3	E	24
C	Little Sugar Creek @ Archdale Rd.	Yes	110.3	72.7	124	29	2.5	1.2	E	39
Rural	Sal's Branch	No	0.5	1.0	2	3	0.4		E4	<10
Rural	Humpy Creek	Yes	2.7	1.5	2	4	0.4	1.7	E5	<10
Rural	Dutchmans	Yes	8.9	4.2	2	7	0.6	1	C5	<10
Rural	Mill Creek	No	12.2	4.3	8	7	0.6		E4	<10
Rural	Upper Mitchell River	No	16.8	5.8	10	9	0.7		B4c	<10
Rural	Norwood Creek	Yes	18.6	9.2	7	10	0.9	1.1	E5	<10
Rural	North Pott's Creek	Yes	24.9	8.3	14	8	1.1	1.7	E5	<10
Rural	Tick Creek	Yes	40.1	18.0	19	12	1.5	1.3	E	<10
Rural	Moon Creek	Yes	77.4	15.1	20	10	1.5	1.8	E5	<10
Rural	Long Creek	Yes	82.4	18.1	29	12	1.5	1.4	E5	<10
Rural	Little Yadkin River	Yes	110.9	43.6	63	24	1.8	1.4	G5	<10
Rural	Mitchell River	Yes	204.1	35.0	76	23	1.5	1.6	C	<10
Rural	Fisher River	Yes	331.5	53.7	104	31	1.7	1.4	C3	<10

*C=UNC Charlotte and Charlotte Storm Water Services; NCSU = NC State University; Rural = from Harman et al., 1999.
** Ten years of gage data not available for flood frequency analysis.
*** Gage no longer in place. Discharge calculated using Manning's equation.

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